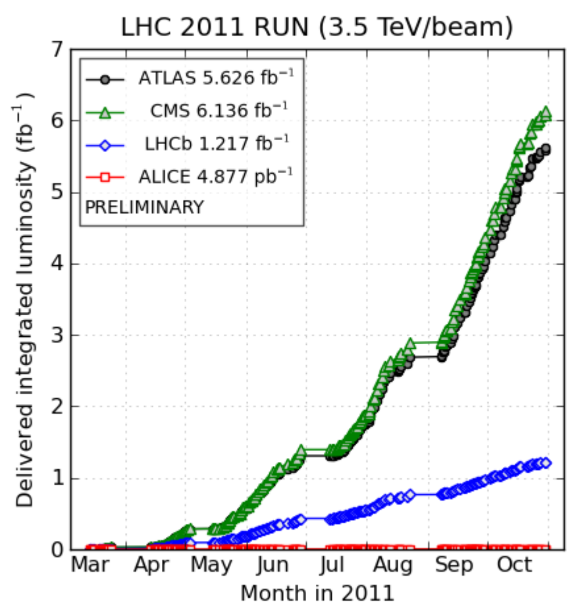
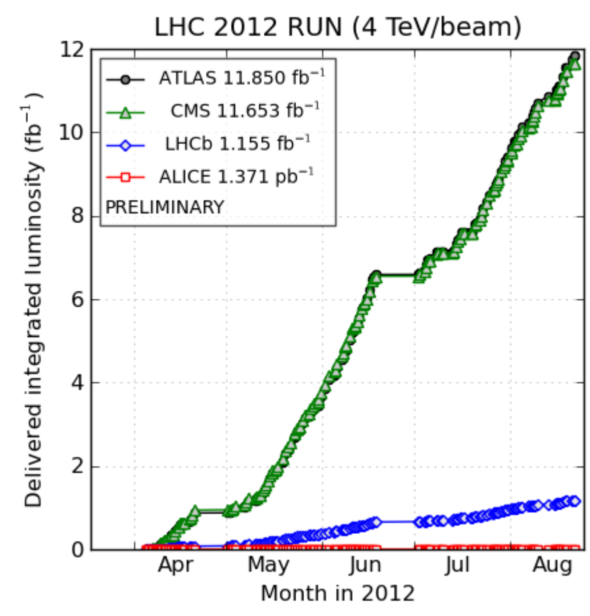
WW/HWW in the dilepton + MET final state in the CMS experiment at the LHC

Clara Jordá – 28th August

LHC accelerator and CMS detector

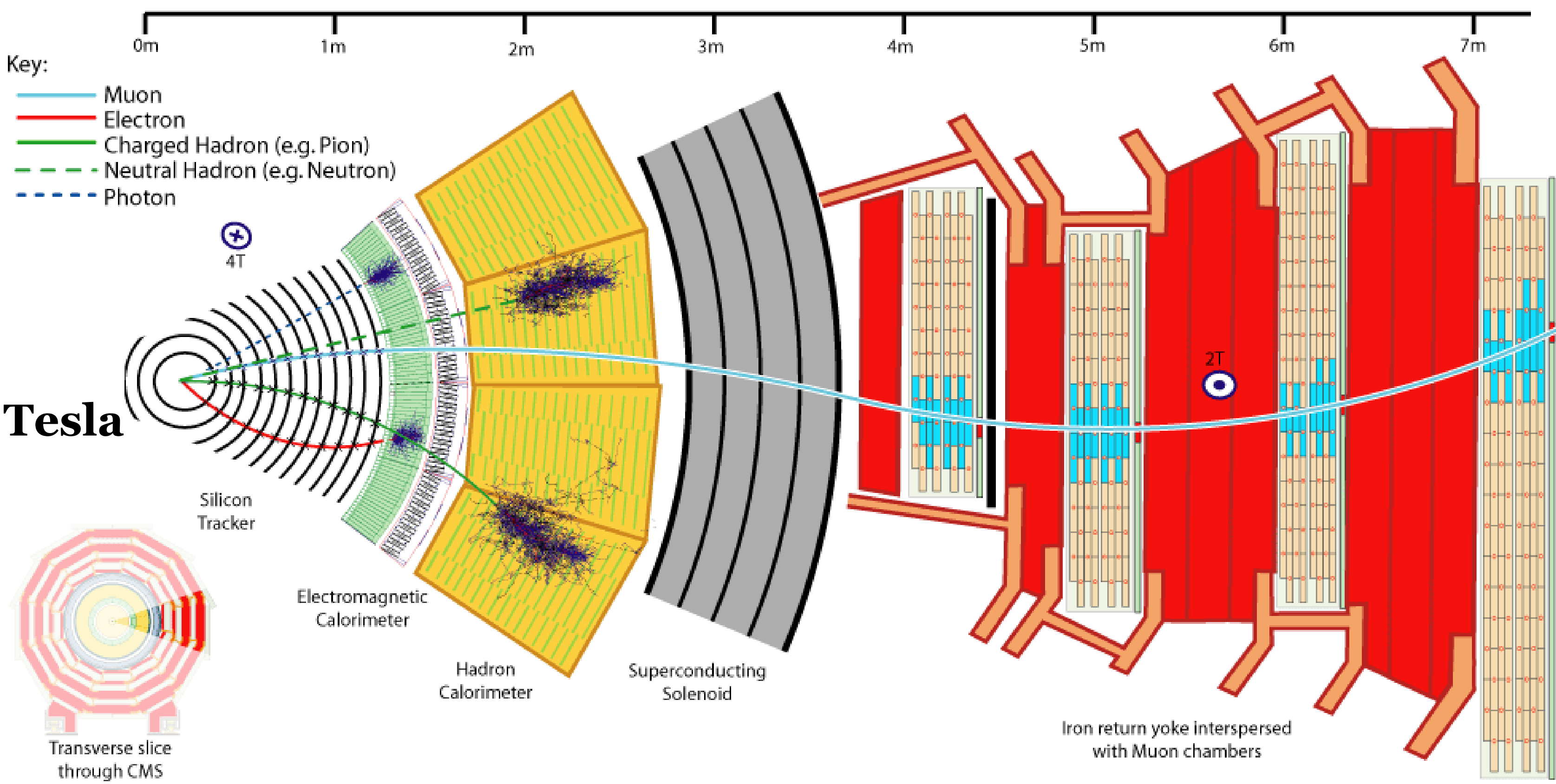
- Large Hadron Collider: proton-proton collisions (also Heavy Ions)
  - Huge and diverse physics programme
    - Searches: Higgs, SUSY, extra-dimensions, etc
    - Precision measurements: EWK, Top physics, etc
  - Machine records
    - 2011 and 2010 at 7 TeV (5 /fb) & 2012 at 8 TeV (near 13 /fb)
    - Highest instantaneous luminosity delivered (up to $7{\cdot}10^{33}$ $cm^{-2}s^{-1}$)





LHC accelerator and CMS detector

- CMS: Compact Muon Solenoid: multipurpose detector



B = 4 Tesla

Muon
Tracker + Muon System

Charged Hadron
Tracker + Hadron Cal.

Photon
Electromagnetic Cal.

Electron
Tracker + Electromagnetic Cal.

Neutral Hadron
Hadron Cal.

WW cross section measurement

- Introduction
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- Selection
- Efficiency Measurements
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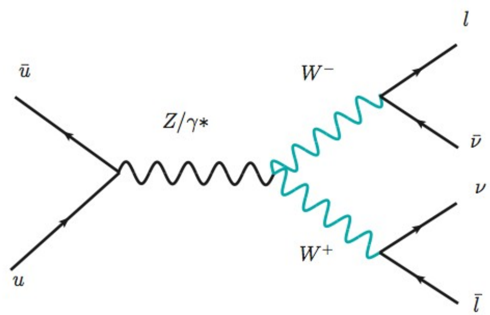
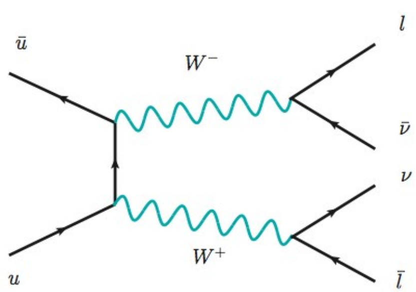
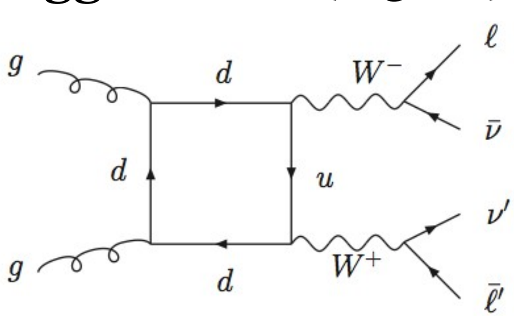
Introduction

- Production modes
  - $q\bar{q} \rightarrow WW$ (97 %)





  - $gg \rightarrow WW$ (3 %)



- Test of the Standard Model at highest energy ever at the LHC

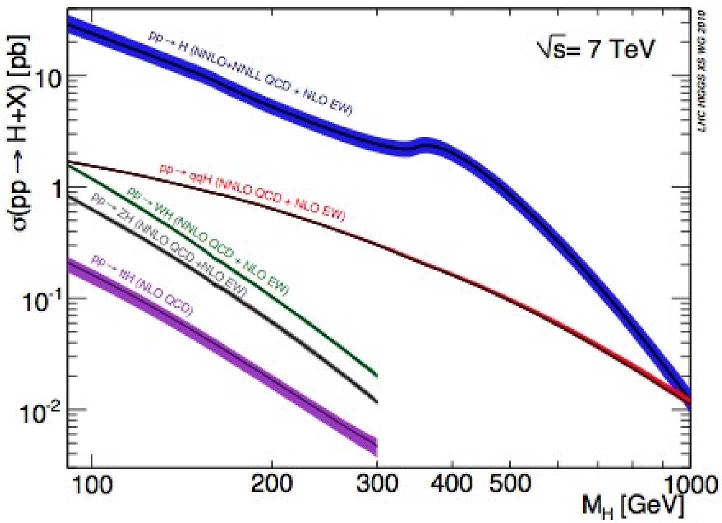
$\sqrt{s}$ (TeV)	$\sigma_{\rm LO}$ WW (pb)	$\sigma_{\rm NLO}$ WW (pb)
7	29.51	47.04 pb $\binom{+4.3\%}{-3.2\%}$
8	35.56	57.25 pb $\binom{+4.1\%}{-2.8\%}$
10	48.07	78.80 pb $\binom{+3.6\%}{-2.5\%}$
14	74.48	124.31 pb $\binom{+2.8\%}{-2.0\%}$

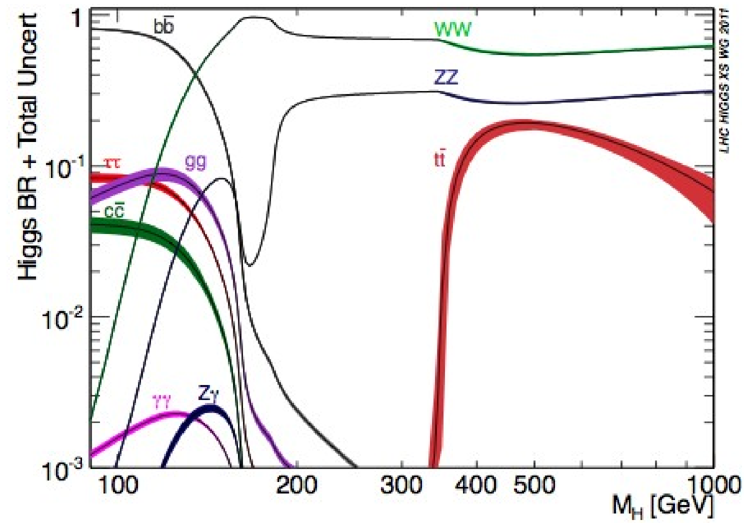
- Trilinear Gauge Couplings (TGC) measurements
  - Anomalous values for these couplings from expectations could be a handle of new physics

$$\begin{aligned}\mathcal{L}_{WWV} = i g_{WWV}\; & g_1^V \left(W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}\right) V^\nu \\ & + k_V W^+_\mu W^-_\nu V^{\mu\nu} \\ & + \frac{\lambda_V}{m_W^2} W_\mu^{+\nu} W_\nu^{-\rho} V_\rho^\mu)\end{aligned}$$

WW cross section measurement

- WW is also the main irreducible background for Higgs searches and measurements in the H → WW channel





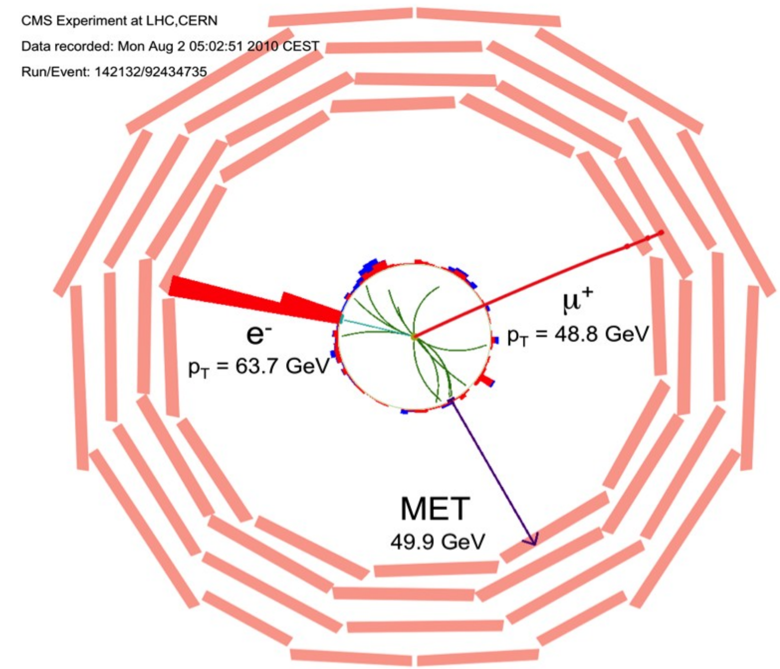
- Both WW and H → WW are almost identical in terms of kinematics, but it can be separated by the azimuthal angle between leptons, Δϕ
  - Small values for Higgs events, W bosons come from a 0-spin particle for mH > 160 GeV
  - Large values for WW events, leptons tend to be emitted back to back

WW cross section measurement

- Experimental Signature for WW → *llνν*
  - Two high p_T leptons with opposite sign
  - Transverse missing E_T
  - Low hard jet activity
- Background:
  - Drell-Yan, ttbar, tW, W+jets, W+γ*

    → from control regions on Data
  - WZ/ZZ, Wγ

    → from MC



- Common selection and strategy for WW cross section measurement and H → WW searches
  - After selection for WW measurement, apply dedicated cuts for Higgs searches in pT leptons, Δϕ, mll and mT

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Data and MC Samples

- Full 2011 Data – 4.92 /fb

Table 2: Datasets used to analyze 2011 data.

/SingleElectron/Run2011A-***/AOD
/SingleMu/Run2011A-***/AOD
/DoubleElectron/Run2011A-***/AOD
/DoubleMu/Run2011A-***/AOD
/MuEG/Run2011A-***/AOD
/SingleElectron/Run2011B-PromptReco-v1/AOD
/SingleMu/Run2011B-PromptReco-v1/AOD
/DoubleElectron/Run2011B-PromptReco-v1/AOD
/DoubleMu/Run2011B-PromptReco-v1/AOD
/MuEG/Run2011B-PromptReco-v1/AOD
*** == PromptReco-v[4,6], May10ReReco-v1, 05Aug2011-v1

- Double lepton and single leptons triggers on Data
- For simulated events, no trigger selection is applied
    - Weight for data efficiencies

- MC Production: mainly Madgraph and Powheg

Table 1: Summary of simulated datasets. The corresponding production cross-sections multiplied by branching ratio for the background samples are also listed.

background samples	σ[pb] $\cdot$ BR
/TTTo2L2Nu2B_7TeV-powheg-pythia6/***1/AODSIM	17.1
/T_TuneZ2_tW-channel-DR_7TeV-powheg-tauola/***1/AODSIM	7.87
/Tbar_TuneZ2_tW-channel-DR_7TeV-powheg-tauola/***1/AODSIM	7.87
/T_TuneZ2_t-channel_7TeV-powheg-tauola/***1/AODSIM	41.92
/Tbar_TuneZ2_t-channel_7TeV-powheg-tauola/***1/AODSIM	22.65
/T_TuneZ2_s-channel_7TeV-powheg-tauola/***1/AODSIM	3.19
/Tbar_TuneZ2_s-channel_7TeV-powheg-tauola/***1/AODSIM	1.44
/DYToEE_M-20_CT10_TuneZ2_7TeV-powheg-pythia/***1/AODSIM	1666
/DYToMuMu_M-20_CT10_TuneZ2_7TeV-powheg-pythia/***1/AODSIM	1666
/DYToTauTau_M-20_CT10_TuneZ2_7TeV-powheg-pythia-tauola/***2/AODSIM	1666
/DYToEE_M-10To20_TuneZ2_7TeV-pythia6/***1/AODSIM	3319
/DYToMuMu_M-10To20_TuneZ2_7TeV-pythia6/***1/AODSIM	3319
/DYToTauTau_M-10To20_CT10_TuneZ2_7TeV-powheg-pythia-tauola/***2/AODSIM	3319
/WZJetsTo3LNu_TuneZ2_7TeV-madgraph-tauola/***1/AODSIM	18.2
/ZZ_TuneZ2_7TeV_pythia6_tauola/***1/AODSIM	7.67
/WJetsToLNu_TuneZ2_7TeV-madgraph-tauola/***1/AODSIM	31314
/WGToENuG_TuneZ2_7TeV-madgraph/***1/AODSIM	165
/WGToMuNuG_TuneZ2_7TeV-madgraph/***1/AODSIM	14.85
/WGToTauNuG_TuneZ2_7TeV-madgraph-tauola/***1/AODSIM	14.85
/WGstarToLNu2Mu_TuneZ2_7TeV-madgraph-tauola/***1/AODSIM	1.60
/WGstarToLNu2E_TuneZ2_7TeV-madgraph-tauola/***1/AODSIM	5.55
signal samples	
/WWJetsTo2L2Nu_TuneZ2_7TeV-madgraph-tauola/***1/AODSIM	4.79
/GluGluToWWTo4L_TuneZ2_7TeV-gg2ww-pythia6/***1/AODSIM	0.153
*** == Fall11-PU_S6_START42_V14B-v	

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WW cross section measurement

Selection	Cut	Purpose
μ sel. e sel.	Only 2 high p_T (20 GeV) isolated leptons with opposite sign	Reduce diboson WZ and ZZ and W+jets and QCD
	Reject events consistent with Z boson mass for SF channels	Reduce Drell–Yan and peaking WZ / ZZ
MET sel.	Require high missing transverse energy, MET	Reduce Drell–Yan
Veto sel.	Veto events with high p_T jets (30 GeV) Veto events with soft muon or low p_T jets b-tagged	Reduce top quark backgrounds: ttbar and single top, tW
Others	Kinematical cuts i.e. on $p_T(ll)$	Reduce remaining Drell-Yan and W+jets

SF : Same flavour final state
OF: Opposite flavour final state

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Signal efficiency

Cross section estimated as:

$$\sigma_{\mathrm{WW}} = \frac{\mathrm{N_{Data}} - \mathrm{N_{bkg}}}{\mathcal{L}_{\mathrm{int}} \cdot \epsilon \cdot (3 \cdot \mathrm{BR}(\mathrm{W} \to \ell\bar{\nu}))^2}$$

N_{data}: Data yield
N_{bkg}: Expected Background
L_{int}: Integrated luminosity
ε: signal efficiency
BR: W → lν branching ratio. BR = 0.108

We need to measure correctly the efficiency for signal selection

- Estimated from Monte Carlo simulation
- Correct lepton efficiencies on MC with data measurements with scale factors
- Estimate also the scale factor data to MC for the jet veto efficiency

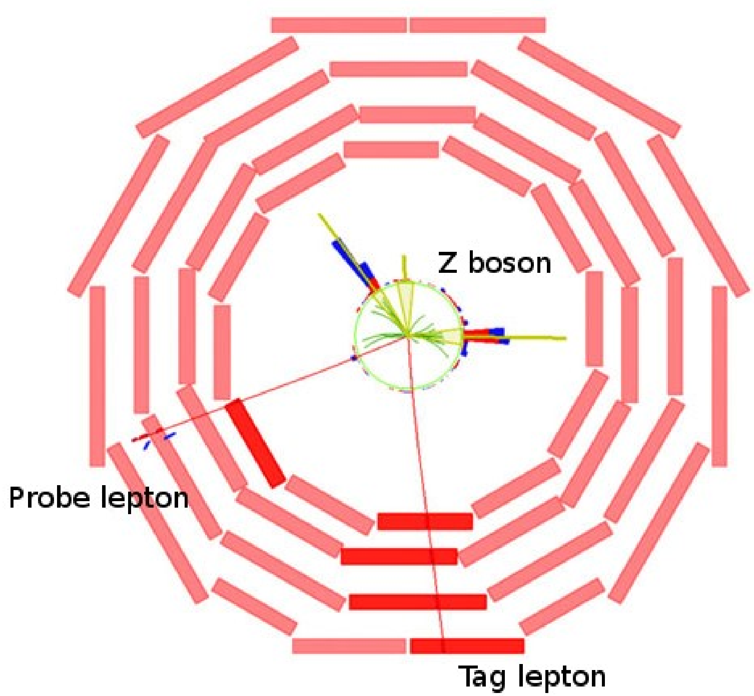
$$\epsilon = A \cdot \epsilon_{\mathrm{trigger}} \cdot \epsilon_{\ell 1\ \mathrm{ID+Iso}} \cdot \epsilon_{\ell 2\ \mathrm{ID+Iso}} \cdot \epsilon_{\mathrm{CJV}} \cdot \epsilon_{\mathrm{other\ cuts}}$$

$$\epsilon = A \cdot \mathrm{w_{trigger}} \cdot (\mathrm{w}_{\mathrm{eff}\ell 1} \cdot \epsilon_{\ell 1\ \mathrm{ID+Iso}}) \cdot (\mathrm{w}_{\mathrm{eff}\ell 2} \cdot \epsilon_{\ell 2\ \mathrm{ID+Iso}}) \cdot (\mathrm{sf_{CJV}} \cdot \epsilon_{\mathrm{CJV}}) \cdot \epsilon_{\mathrm{other\ cuts}}$$

Lepton efficiencies

For lepton efficiency measurements I used the official T&P package

- Z resonance (low-high pT leptons)
- Select one *tag* (tight requirements) lepton, matched to the trigger used to select the sample
- Use as *probe* the other leg in the resonance



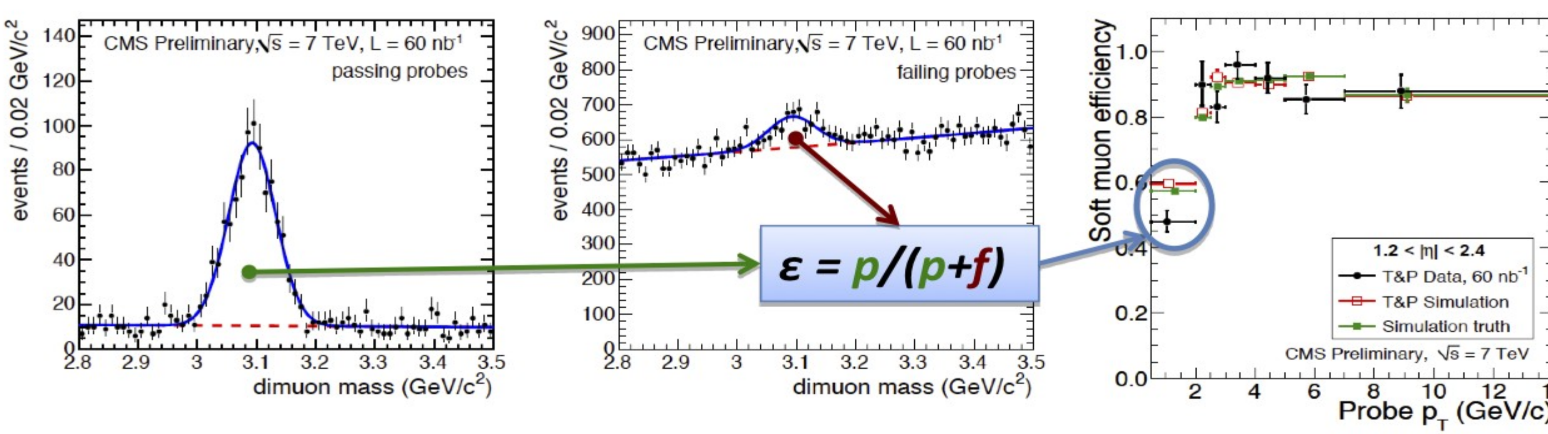
Lepton efficiencies

- Maximum likelihood simultaneous fit for the signal and background events, for the passing and failing probes
- Definition of a Particle Data Function for signal and another for background events

Passing probes: Nsignal · **efficiency** · signal + NbackgroundPass · backgroundPass

Failing probes: Nsignal · (1 – **efficiency**) · signal + NbackgroundFail · backgroundFail

- This way we extract the number of passing and failing probes and the efficiency of the selection



Lepton efficiencies

Different function fits:

- **Signal** Fit correctly the Z mass peak

$$2 \times \frac{1}{(\mathrm{m}-\bar{\mathrm{m}})^2+\frac{1}{4}\mathrm{g}^2} \otimes \exp\left(-\frac{1}{2}\left(\frac{m}{s}\right)^2\right)$$

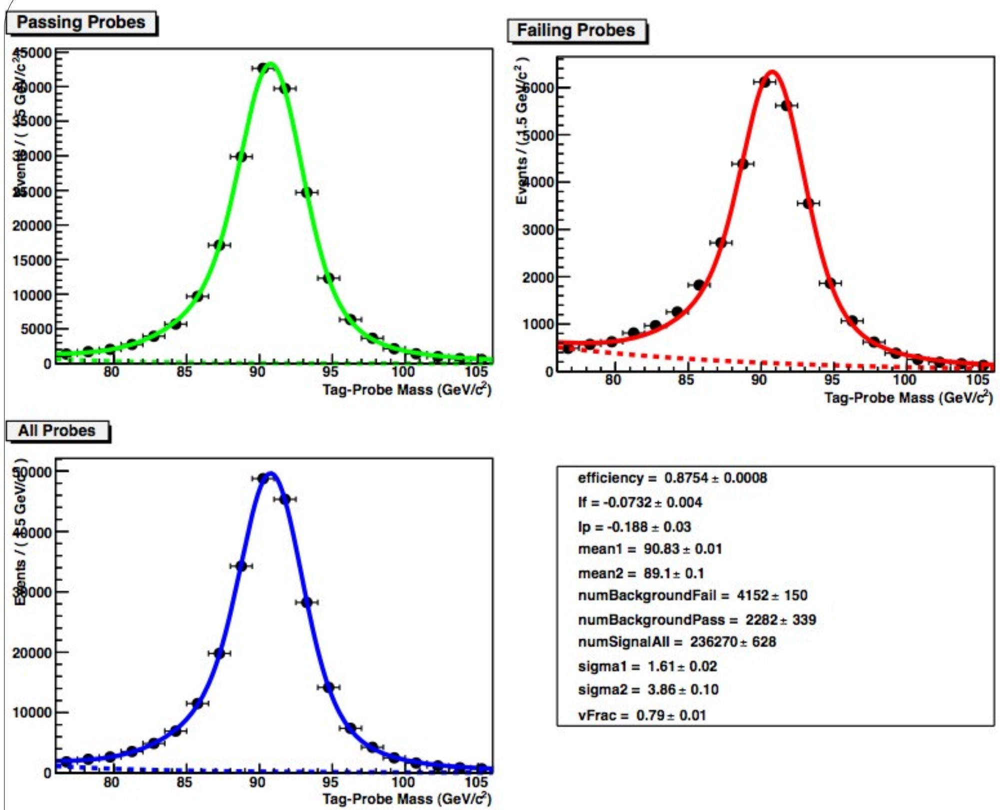
muons
2 Voigtian (peak + resolution effects)

$$(\mathrm{m}-\bar{\mathrm{m}}) \cdot \exp\left(\frac{-(m-\bar{m})^2}{\sigma_S^2+\alpha_S(m-\bar{m})^2}\right)$$

electrons
Asymmetric exponential
account for energy looses

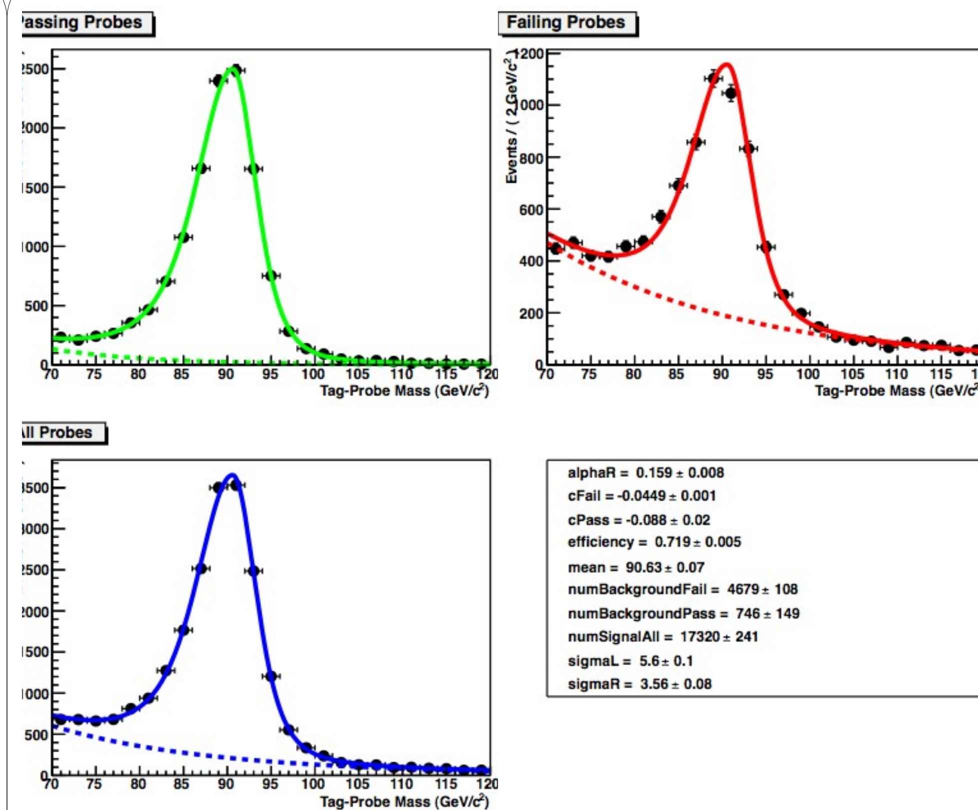
- **Background** Combinatorial
  - I used exponential backgrounds for both muons and electrons
- Detailed study of the functions and parameter
  - Same for Data & MC : part of the systematics cancel
  - Assign a systematic for the differences – less than 1% for pT > 20 GeV

Lepton efficiencies



muons

Signal: 2 Voigtian (peak + resolution effects)
Back: Exponential



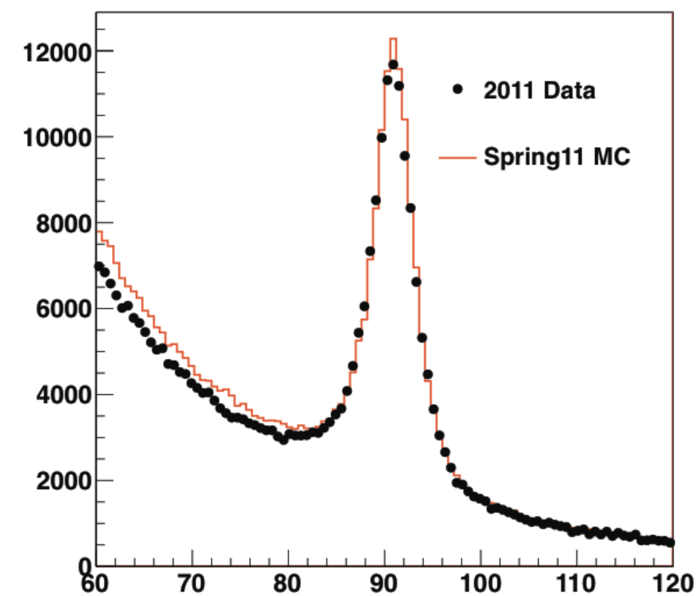
electrons

Signal: Asymmetric exponential
Back: Exponential

Lepton efficiencies

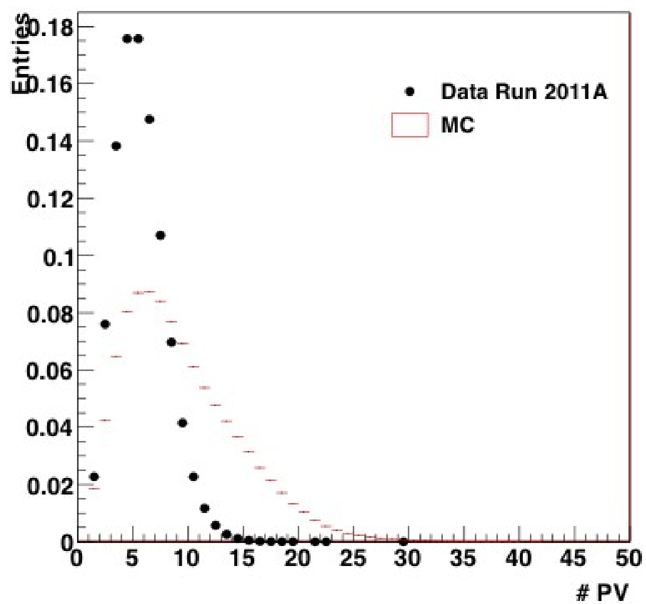
- For MC efficiencies I used a mixture of Drell-Yan, ttbar and W+jets samples
  - Created with the correct number of events to account for the same integrated luminosity as for data → similar statistics

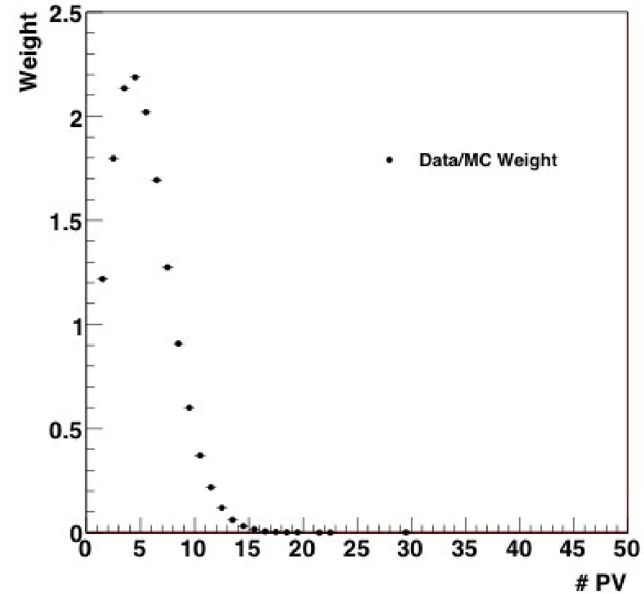
- Increase of the instantaneous luminosity on 2011 data after the LHC Technical Stop on September – Runs 2011A & 2011B
  - To cope with the difference in the # PV, assign a per-event weight
  - Use this weight in the efficiency fit
  - Separately for Run2011A and Run2011B



Example from early 2011 Data
Not re-weighted for pile-up

Lepton efficiencies

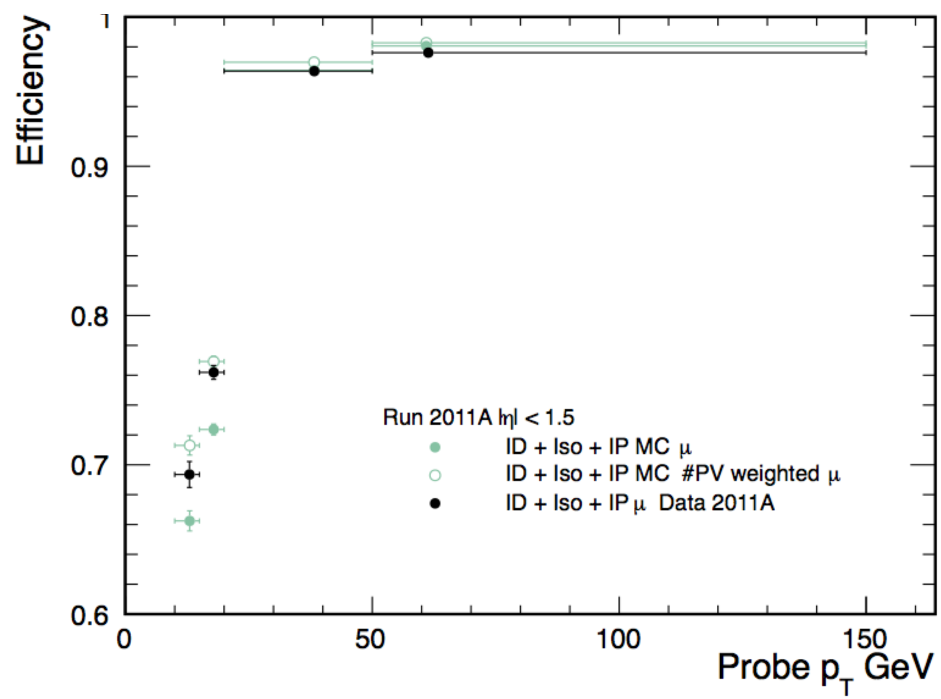




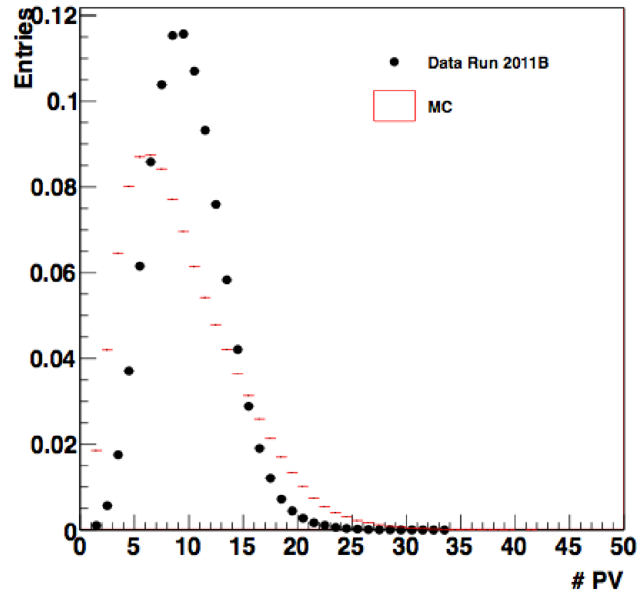
- For **Run2011A**, the MC presents higher multiplicity for the pile-up

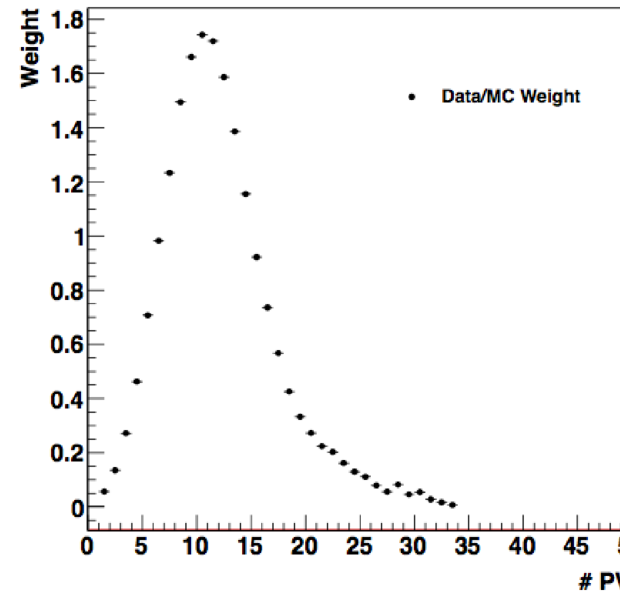
- Weights are > 1 for low nVtx events

- Weighted MC recover the Data efficiency
  - in this case, higher than the efficiency not-reweighted



Lepton efficiencies

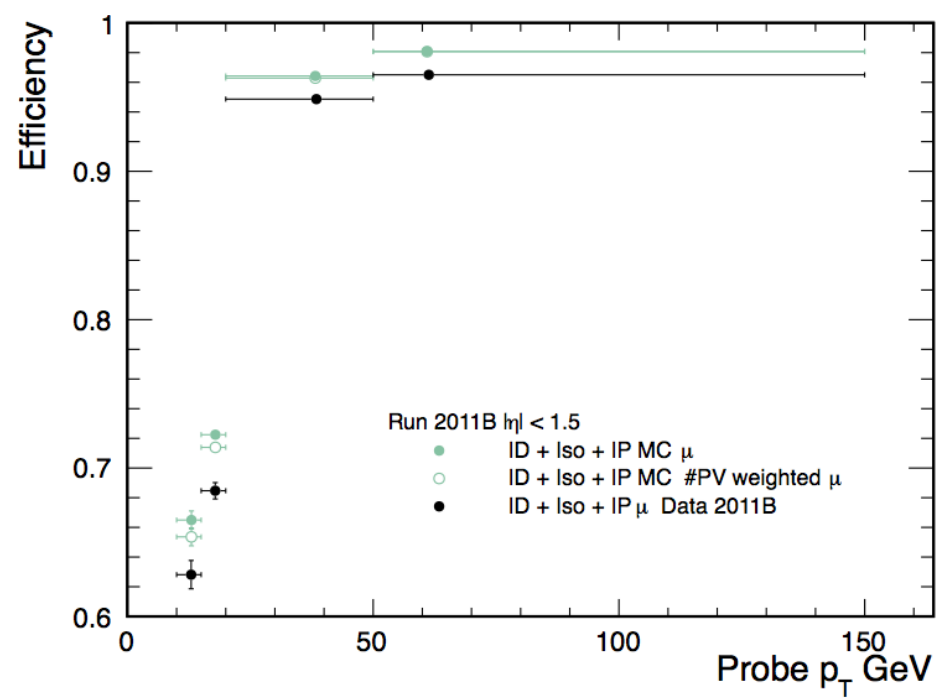




- For **Run2011B**, the MC presents lower multiplicity for the pile-up than Data

- Weights are > 1 for higher nVtx events

- Weighted MC recover the Data efficiency
  - in this case, lower than the efficiency not-reweighted



Lepton efficiencies: identification

- Estimate the Data to MC lepton efficiencies scale factors for the two 2011 periods: 2011A and 2011B
  - (p_T,η) dependant
  - Scale factors close to one for the majority of cases

Table 7: Muon identification efficiency data/simulation scale factors.

	p_T range [GeV]	$\|\eta\| < 1.48$	$\|\eta\| > 1.48$
2011A	$20 < p_T < 50$	0.994 ± 0.000	0.995 ± 0.001
	$50 < p_T$	0.993 ± 0.001	0.991 ± 0.002
2011B	$20 < p_T < 50$	0.985 ± 0.000	0.963 ± 0.001
	$50 < p_T$	0.984 ± 0.001	0.965 ± 0.003

Table 8: Electron identification efficiency data/simulation scale factors.

	p_T range [GeV]	$\|\eta\| < 1.4442$	$1.4442 < \|\eta\| < 1.556$	$\|\eta\| > 1.556$
2011A	$20 < p_T < 25$	0.959 ± 0.007	1.041 ± 0.051	1.015 ± 0.014
	$25 < p_T < 50$	0.990 ± 0.000	1.014 ± 0.008	1.006 ± 0.002
	$50 < p_T$	0.986 ± 0.002	1.012 ± 0.020	1.014 ± 0.030
2011B	$20 < p_T < 25$	0.947 ± 0.008	0.950 ± 0.053	1.006 ± 0.019
	$25 < p_T < 50$	0.988 ± 0.006	1.007 ± 0.007	1.010 ± 0.003
	$50 < p_T$	0.982 ± 0.002	0.992 ± 0.011	0.999 ± 0.006

- The simulated event is finally weighted to account for the efficiencies:

$$\mathrm{w_{eff}} = \frac{\mathrm{sf_A \cdot L_{intA} + sf_B \cdot L_{intB}}}{\mathrm{L_{intA} + L_{intB}}}$$

Lepton efficiencies: trigger

- Measure the per-leg trigger efficiency using Tag & Probe on Data events
  - (p_T, η) dependant
- Weight MC events for the trigger efficiency taking into account the (p_T, η) of both leptons

$$
\begin{aligned}
\varepsilon_{\ell\ell'}(p_T,\, \eta,\, p'_T,\, \eta') \;=\; & 1 - [(1-\varepsilon_{\mathrm{D,leading}}(p_T,\, \eta))(1-\varepsilon_{\mathrm{D,leading}}(p'_T,\, \eta')) \\
& + \varepsilon_{\mathrm{D,leading}}(p_T,\, \eta)(1-\varepsilon_{\mathrm{D,trailing}}(p'_T,\, \eta')) \\
& + \varepsilon_{\mathrm{D,leading}}(p'_T,\, \eta')(1-\varepsilon_{\mathrm{D,trailing}}(p_T,\, \eta))] \\
& + \varepsilon_{S}(p'_T,\, \eta')(1-\varepsilon_{\mathrm{D,trailing}}(p_T,\, \eta)) \\
& + \varepsilon_{S}(p_T,\, \eta)(1-\varepsilon_{\mathrm{D,trailing}}(p'_T,\, \eta'))
\end{aligned}
$$

Both legs pass the double lepton trigger

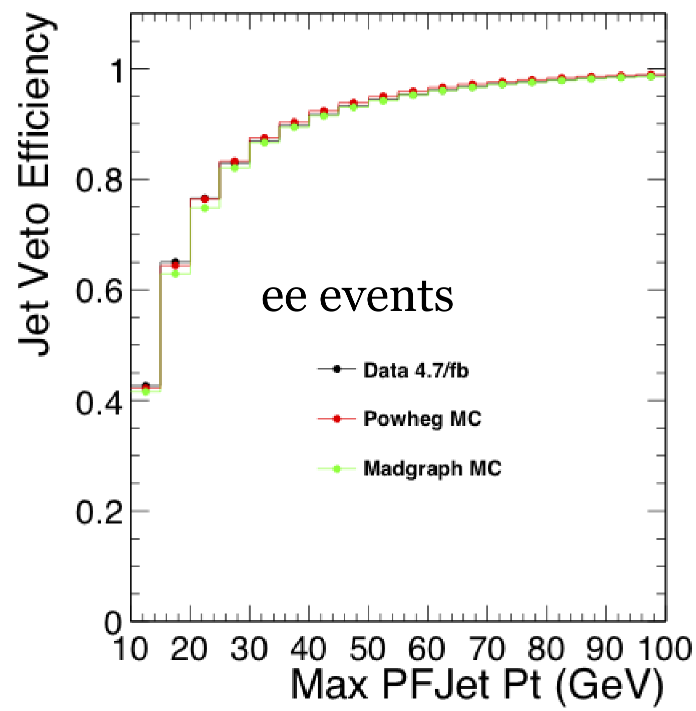
One leg passes if other fails the double

- Signal efficiency with respect to offline selection is nearly 97%

Channel	Trigger Efficiency (%)
All ($p_T > 20/20$ GeV)	96.88
$\mu\mu$ ($p_T > 20/20$ GeV)	98.49
ee ($p_T > 20/20$ GeV)	98.54
μe ($p_T > 20/20$ GeV)	95.23
eμ ($p_T > 20/20$ GeV)	96.45

Jet veto efficiency

- We measured the jet veto efficiency on Data events and compare with MC
- Select a clean Z sample
  - Do not apply MET cuts
  - Look at the Z boson mass window
- Jet veto efficiency for signal on Data events
  - $\varepsilon_{WW} = \varepsilon_{WW}^{MC} (\varepsilon_Z^{data} / \varepsilon_Z^{MC})$
- Scale factor found to be near to one



samples	all vtx bins	nVtx <= 5	5 < nVtx < 10	nVtx >= 10
		ee Final State		
data	0.83 ± 0.00	0.84 ± 0.00	0.83 ± 0.00	0.81 ± 0.00
powheg MC	0.83 ± 0.00	0.85 ± 0.00	0.83 ± 0.00	0.80 ± 0.00
madgraph MC	0.82 ± 0.00	0.84 ± 0.00	0.82 ± 0.00	0.79 ± 0.00
data/powheg MC	1.00 ± 0.00	0.99 ± 0.00	1.00 ± 0.00	1.01 ± 0.00
data/madgraph MC	1.01 ± 0.00	1.00 ± 0.00	1.01 ± 0.00	1.03 ± 0.00
		$\mu\mu$ Final State		
data	0.83 ± 0.00	0.85 ± 0.00	0.84 ± 0.00	0.82 ± 0.00
powheg MC	0.84 ± 0.00	0.85 ± 0.00	0.84 ± 0.00	0.81 ± 0.00
madgraph MC	0.82 ± 0.00	0.84 ± 0.00	0.83 ± 0.00	0.79 ± 0.00
data/powheg MC	1.00 ± 0.00	0.99 ± 0.00	0.99 ± 0.00	1.01 ± 0.00
data/madgraph MC	1.01 ± 0.00	1.01 ± 0.00	1.01 ± 0.00	1.03 ± 0.00

Table 11: The jet veto efficiency and its data/simulation ratios on Z events, using particle flow jets with the corrections described in Section 3.7. The jet veto thresold is 30 GeV.

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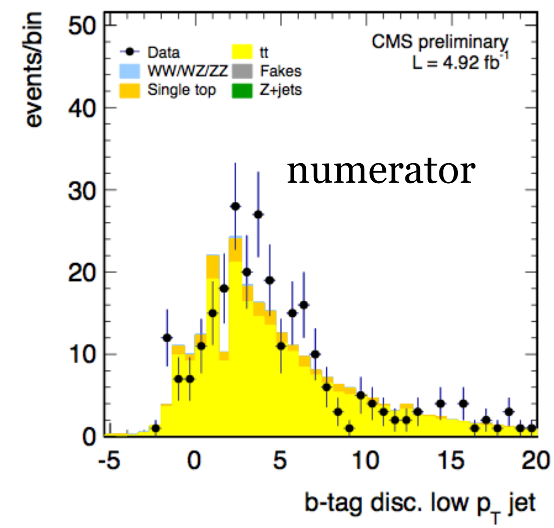
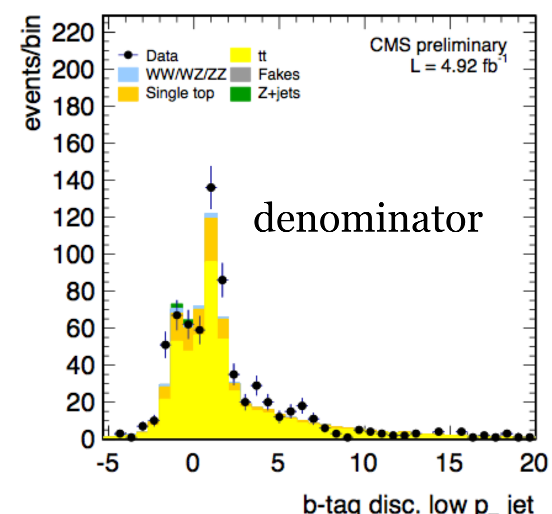
Top background estimation

- Top reduction: apply soft muon veto and low p_T jet top-tagging → tag a soft jet
- **Measure the efficiency to tag a soft jet**
- Select a pure ttbar events sample **on Data**
  - Require exactly one jet with $p_T > 30$ GeV and TCHE > 2.1
  - Count how many of these events also pass the soft jet or soft muon tagging
    - Subtract non ttbar contribution based on Data and MC predictions
- Tagging efficiency 34%, consistent with MC





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    - Subtract non ttbar contribution based on Data and MC predictions
- Tagging efficiency 34%, consistent with MC

	Value
$N_{\mathrm{tag}}^{\mathrm{control\ tt\ MC}}$	264.2 ± 1.6
$N^{\mathrm{control\ tt\ MC}}$	772.3 ± 2.7
$\epsilon_{\mathrm{top-tag}}^{\mathrm{tt\ MC}}(\%)$	34.2 ± 0.2
$N_{\mathrm{tag}}^{\mathrm{control\ tW\ MC}}$	31.1 ± 1.7
$N^{\mathrm{control\ tW\ MC}}$	218.9 ± 4.6
$\epsilon_{\mathrm{top-tag}}^{\mathrm{tW\ MC}}(\%)$	14.2 ± 0.8
$N^{\mathrm{Data\ control}}$	1091
$N_{\mathrm{tag}}^{\mathrm{Data\ control}}$	322
$N^{\mathrm{bkg\ control}}$	251.8 ± 4.9
$N_{\mathrm{tag}}^{\mathrm{bkg\ control}}$	33.1 ± 1.7
$\epsilon_{\mathrm{top-tag}}^{\mathrm{Data}}\ (\%)$	34.4 ± 2.5

Top background estimation

- Next step is to **estimate the final top veto efficiency**
  - Take into account tW and ttbar fraction of events before applying the veto: $f_{tt} = N_{tt}/(N_{tt}+N_{tW})$ and $f_{tW} = (1 - f_{tt})$
  - The tW process can have two b-quarks in the final state at NLO
    - Consider the fraction *x* of tW events that have two taggeable legs, taken as the $\varepsilon_{top\text{-}tag}$ for tW MC events: x = 0.14

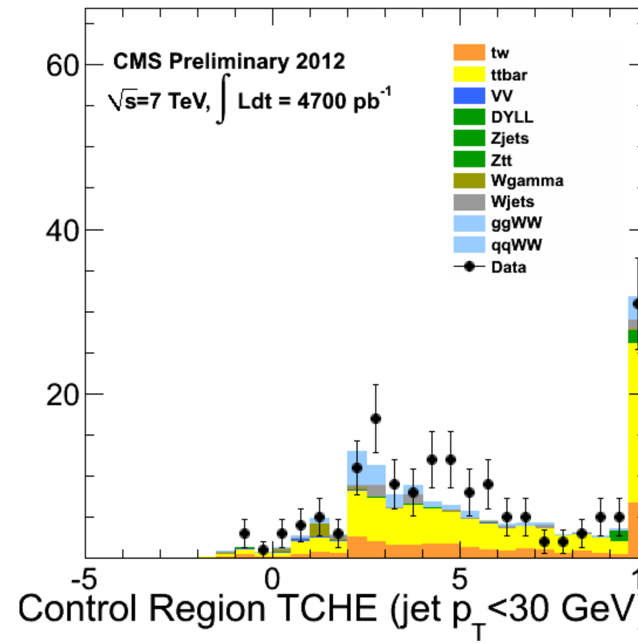
- The final top veto efficiency in the zero jet bin is expressed as:

$$\epsilon^{0-\mathrm{jet}}_{\mathrm{top-tag}} = \underbrace{(\underbrace{f_{tt}}_{\text{tt}} + \underbrace{f_{\mathrm{tW}} \cdot x}_{\text{tW with 2b}}) \cdot (1 - (1 - \epsilon_{\mathrm{top-tag}})^2)}_{\text{Two taggeable legs}} + \underbrace{\underbrace{f_{\mathrm{tW}} \cdot (1 - x)}_{\text{tW with 1b}} \cdot \epsilon_{\mathrm{top-tag}}}_{\text{One taggeable leg}}$$

Top background estimation

- The final step is to extrapolate the number of top events from a control region to the zero jet region
- Select control region by inverting the top veto
  - Subtract the non top contributions
  - Correct for tagging efficiency to find the number expected to fail the soft jet veto

$$N^{top}_{WWregion} = (N^{data}_{topTag}{}^{*} - N^{data}_{other-bkg}{}^{*})\frac{1-\epsilon^{data}_{topTag}{}^{*}}{\epsilon^{data}_{topTag}}$$



	Value
$N^{\mathrm{Datacontrol}}$	1091
$N^{\mathrm{Datacontrol}}_{\mathrm{tag}}$	322
$\epsilon^{\mathrm{Data}}_{\mathrm{top-tag}}$ (%)	34.4 ± 2.5 *
$\epsilon^{\mathrm{tW}}_{\mathrm{top-tag}}$	0.14 ± 0.01
f_{tt} (%)	66 ± 11
Tagging efficiency 0-jet, $\epsilon^{\mathrm{0-jet}}_{\mathrm{top-tag}}$ (%)	50.5 ± 3.8
Top-tagged events in data, $\mathrm{N}^{\mathrm{Data-control}}_{\mathrm{btag}}$	162 *
Background events in control region, $\mathrm{N}^{\mathrm{Bkg-control}}_{\mathrm{btag}}$	30.9 ± 2.9 *
Estimated top events in simulation, $\mathrm{N}^{\mathrm{signal}}_{\mathrm{top\ MC}}$	96.5 ± 2.1
Data-driven top background estimate, $\mathrm{N}^{\mathrm{signal}}_{\mathrm{top\ Data}}$	128.5 ± 23.4
Data/MC Ratio	1.33

- Main systematic coming from ttbar – tW cross section
- Also, statistics from top-tagged control region

Drell-Yan background estimation

- Estimate Drell-Yan contribution from a signal – free region
- We use the $R_{out/in}$ method based on the Z mass window region
  - Estimate the ratio of DY events outside/inside the Z mass region →

$$R_{\mathrm{MC}}^{\mathrm{out/in}} \equiv \frac{N_{DY}^{\mathrm{control,MC}}}{N_{DY}^{\mathrm{signal,MC}}}$$

  - Count the number of events on Data inside that region corrected for:
    - ZZ/WZ diboson (real MET) – MC predicted
    - non-peaking backgrounds as $N_{e\mu}$ Data events – k corrected:

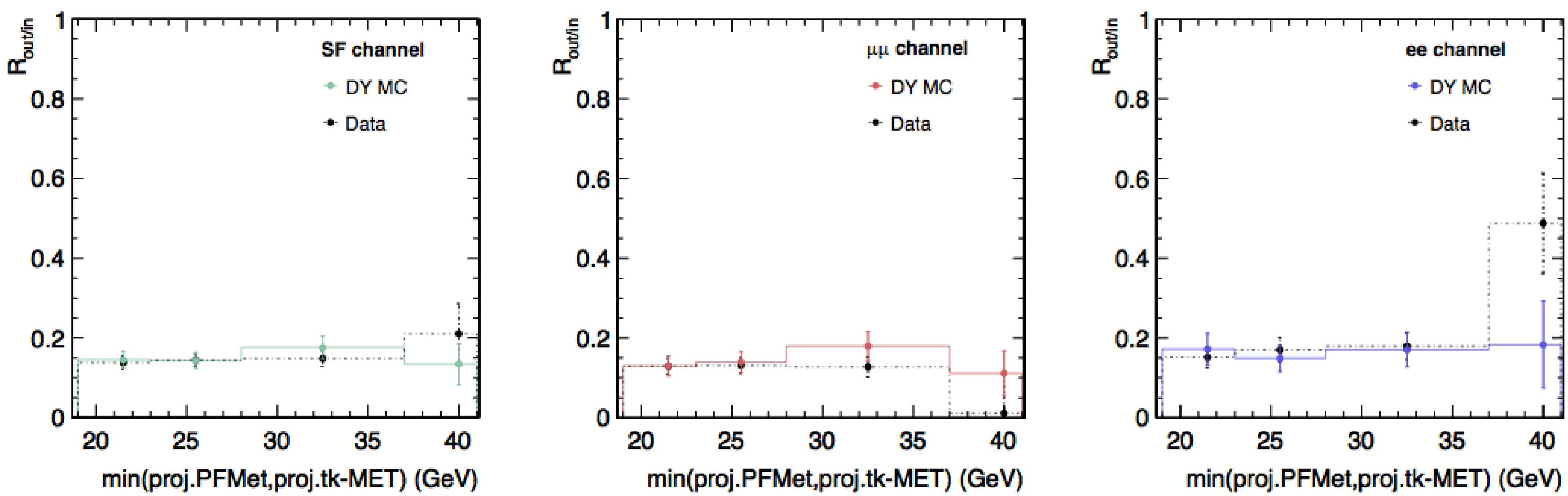
$$k_{SF} = \frac{1}{2} \cdot \left(\sqrt{\frac{N_{\mathrm{ee}}^{\mathrm{control}}}{N_{\mu\mu}^{\mathrm{control}}}} + \sqrt{\frac{N_{\mu\mu}^{\mathrm{control}}}{N_{\mathrm{ee}}^{\mathrm{control}}}} \right)$$

  - Extrapolate to the signal region with the ratio $R_{out/in}$

$$N_{DY}^{\mathrm{signal,data}} = \left(\underline{N_{\ell\ell}^{\mathrm{control,data}}} - \underline{k \cdot N_{\mathrm{e}\mu}^{\mathrm{control,data}}} - \underline{N_{\mathrm{ZV}}^{\mathrm{control,MC}}} \right) \cdot \underline{R_{\mathrm{MC}}^{\mathrm{out/in}}}$$

Drell-Yan background estimation

- Error in the method coming mainly from:
  - Systematic error on R estimation
    - R estimated in different *MET* bins. Error as maximum difference between nominal value and the most deviated one



  - Error in the counted number of events inside the Z mass: data events & peaking backgrounds
  - Estimated final error of about 50%

Drell-Yan background estimation

- Final estimation taken for the total same flavor final state
  - The sum ee + mm states (considering their own R and k parameters) is the same as for the inclusive sf case – no surprises! :-)

Final state	$R_{MC}^{out/in}$	$N_{\ell\ell}^{control,data}$	$N_{DY}^{signal,data}$	$N_{DY}^{signal,MC}$	data/MC
Same flavor	$0.134 \pm 0.051 \pm 0.031$	257	10.98 ± 5.68	3.00 ± 0.93	3.66
$\mu\mu$	$0.112 \pm 0.056 \pm 0.042$	151	4.85 ± 3.52	1.76 ± 0.73	2.76
ee	$0.183 \pm 0.109 \pm 0.034$	106	7.00 ± 4.88	1.24 ± 0.58	5.66

W+jets background estimation

- Contribution from the W+jets: Fake rate (FR) method estimation for both muons and electrons
  - Measure the probability (FR) for a loose lepton object to pass the tight requirements used in the selection, in a QCD data enriched sample
  - Contamination from prompt leptons (W/Z decay) in the FR estimation reduced with some appropriate cuts (m_T < 20 GeV, MET < 20 GeV)

- Background estimation derived by weighting events in a '*tight+fail*' sample
  - '*Fail*' are leptons that pass the loose requirements but fail the tight
  - Use the Fake Rate as weight
  - Contamination from real leptons (which fail the tight cuts) is accounted from data driven methods (prompt rate)

W+jets background estimation

- Systematic error 36%
  - Variation of the nominal estimated value in different background enriched samples defined by the p_T of the leading jet
  - Closure Test on Same Sign Data events

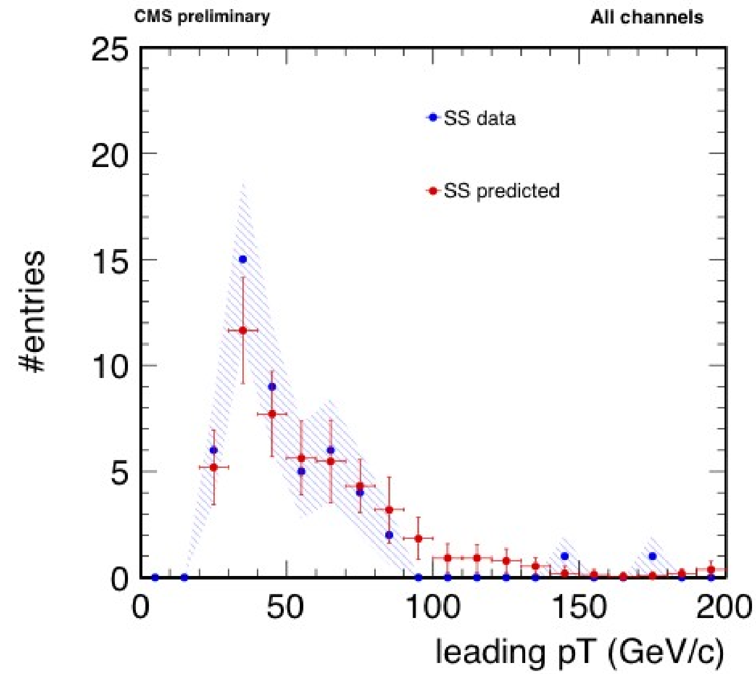
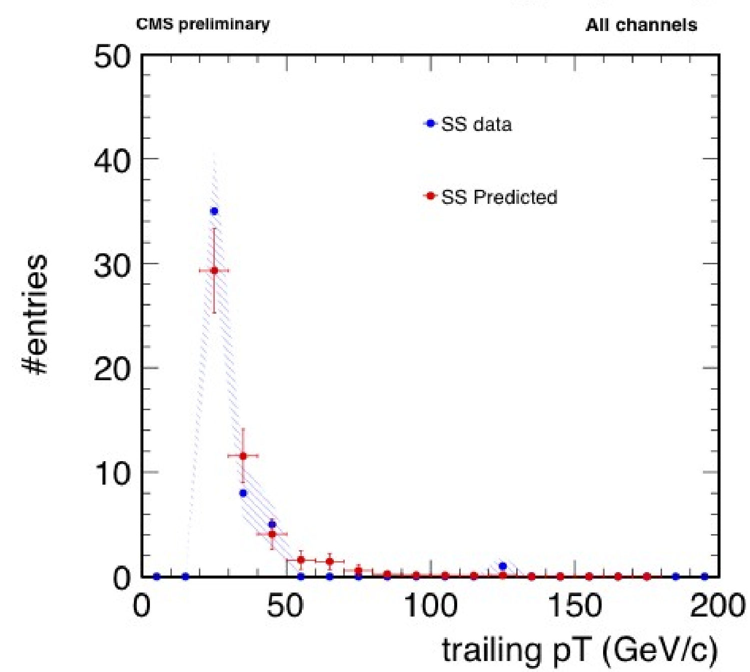


Table 13: W+jets yields in the 0-jet bin. Errors are statistical only.

fake lepton bin	ee channel	μe channel
barrel, $p_T \geq 20$ GeV	7.3 ± 1.1	9.3 ± 1.4
endcap, $p_T \geq 20$ GeV	2.9 ± 0.7	6.8 ± 1.3
total	10.2 ± 1.3	16.2 ± 1.9
fake lepton bin	**eμ channel**	**$\mu\mu$ channel**
barrel, $p_T \geq 20$ GeV	16.3 ± 1.9	5.6 ± 1.6
endcap, $p_T \geq 20$ GeV	10.7 ± 1.8	0.5 ± 1.0
total	27.1 ± 2.6	6.2 ± 1.9



Other backgrounds

- $W\gamma^*$: estimation of the k-factor for the NLO cross section estimation
  - Measure the cross section in a pure signal region
- WZ and ZZ backgrounds are estimated directly from MC simulation
- The Drell-Yan $\rightarrow \tau\tau$ is also estimated from MC
  - Found to be negligible
  - Cross-check result on Data using the embedding method
    - Take kinematics from well reconstructed $Z(\mu\mu)$ events in data
    - Replace muons with taus from simulation and repeat reco
    - Apply analysis selection on new candidates collections to estimate background contribution

WW cross section measurement

- Introduction
- Data and MC Samples
- Selection
- Efficiency Measurements
- Background Estimation
- Systematics
- Results
- Conclusions

WW cross section measurement

Systematic uncertainties

- Lepton momentum scale 2.5 (1.5) % for electrons (muons) on signal efficiency
- Leptons efficiency 1.5% for trigger and 2.0% for identification
- Missing E_T resolution 2.0% for processes with real MET
- Backgrounds normalization
  - W+jets : 36% from closure test and jet p_T threshold variation
  - DY: 50% from $R_{out/in}$ estimation and statistics
  - Top: 18% from control region statistics and ttbar-tW cross section
- PDF Uncertainty 2.3 (0.8)% on signal acceptance for qqWW (ggWW)
- Higher order corrections Found to be 1.5 (30)% for for qqWW (ggWW) varying QCD re-normalization and factorization scales with MCFM
- Luminosity 2.2 % given by CMS

Systematic uncertainties

- Jet veto efficiency 4.6 %, main contribution from the ratio between the WW and Z events jet veto efficiencies in simulation studies Back up
- Pile-up and simulation

  We observed a difference in the signal efficiency when comparing Summer11 and Fall11 Monte Carlo Productions

  - 3% difference coming from differences in the jet veto, top veto and lepton efficiencies – each contributing 1%
  - Summer11: $\varepsilon_{WW} = (3.378 \pm 0.020)$ %
  - Fall11: $\varepsilon_{WW} = (3.279 \pm 0.020)$ %

  Also investigated the effect of the in-time and out-of-time pile up

  To account for the efficiency difference observed in the MC productions we consider a conservative value of 2.3% for the pile up, instead of 1% from standard +/- pile-up shift

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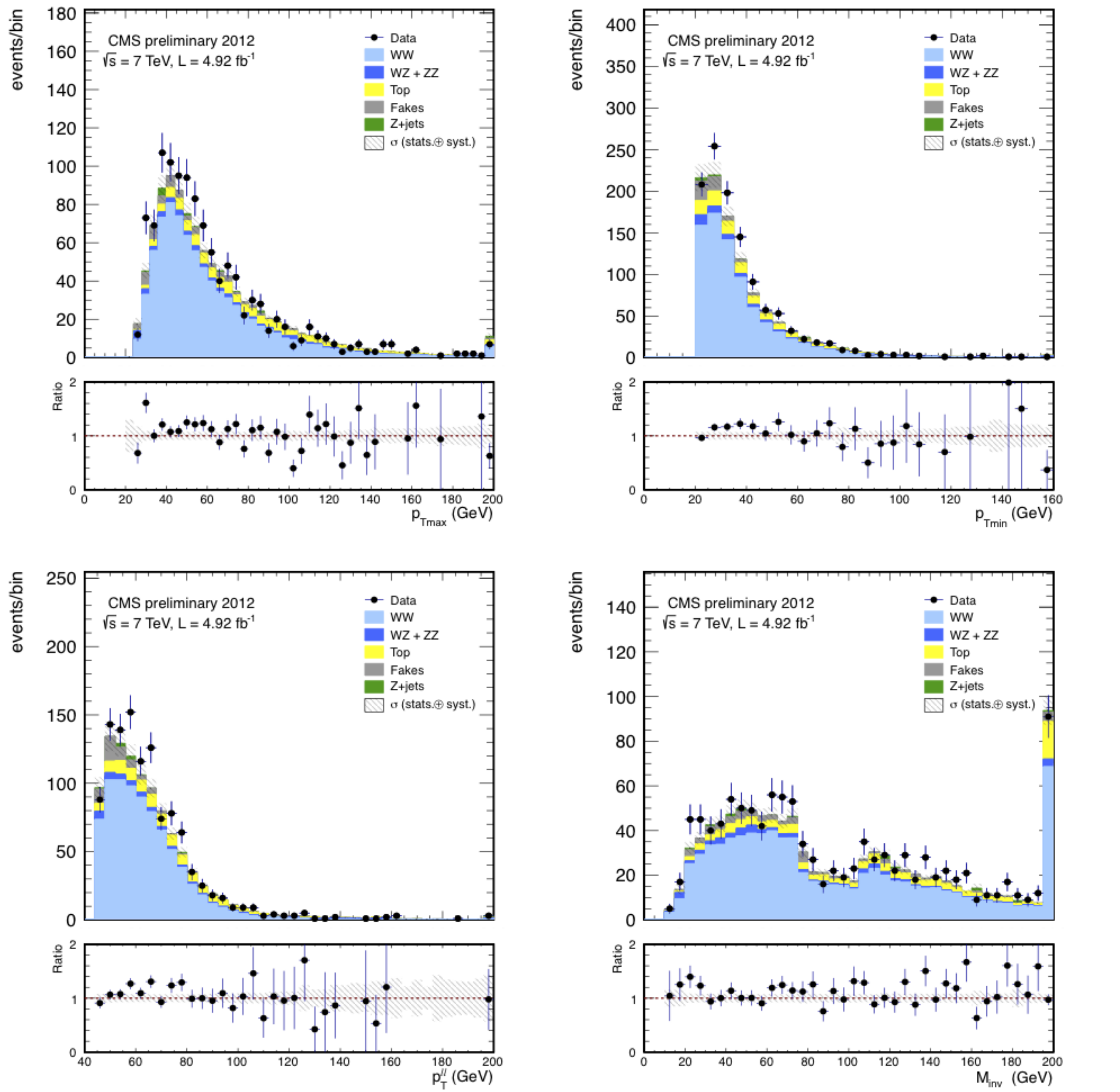
WW cross section measurement

Results for 7 TeV

- Distributions after signal selection for 4.92 /fb

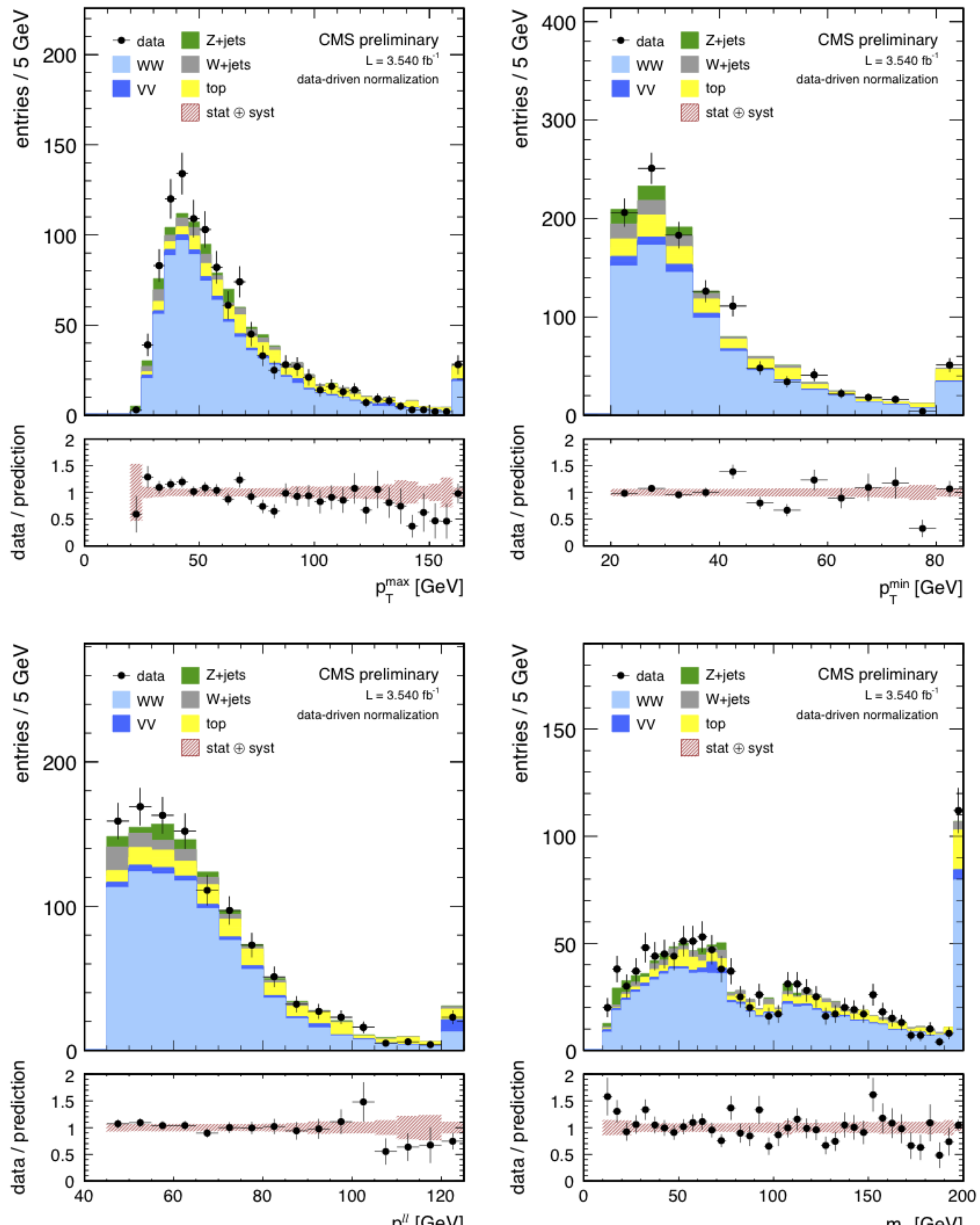
- Backgrounds scaled by control regions on data estimations



WW cross section measurement

Results for 8 TeV

- Distributions after signal selection for 3.54 /fb
- Backgrounds scaled by control regions on data estimations



WW cross section measurement

Results for 7 TeV with 4.92 /fb

Sample	Yield $\pm$ stat. $\pm$ syst.
$gg \to W^+W^-$	$46.0 \pm 0.6 \pm 14.2$
$q\bar{q} \to W^+W^-$	$750.9 \pm 4.1 \pm 53.1$
$t\bar{t}$ +tW	$128.5 \pm 12.8 \pm 19.6$
W+jets	$59.5 \pm 3.9 \pm 21.4$
WZ+ZZ	$29.4 \pm 0.4 \pm 2.0$
Z/γ^*	$11.0 \pm 5.1 \pm 2.6$
$W+\gamma$	$18.8 \pm 2.8 \pm 4.7$
$Z/\gamma^* \to \tau\tau$	$0.0 \pm 1.0 \pm 0.1$
Total Background	$247.1 \pm 14.6 \pm 29.5$
Signal + Background	$1044.0 \pm 15.2 \pm 62.4$
Data	1134

Results for 8 TeV with 3.54 /fb

sample	yield $\pm$ stat. $\pm$ syst.
$gg \to WW$	$43.3 \pm 1.0 \pm 13.4$
$qq \to WW$	$640.3 \pm 4.9 \pm 47.4$
$t\bar{t}$ + tW	$131.6 \pm 12.7 \pm 19.5$
W + jets	$60.0 \pm 4.3 \pm 21.6$
WZ + ZZ	$27.4 \pm 0.5 \pm 2.9$
Z/γ^*	$42.5 \pm 6.0 \pm 9.9$
$W\gamma + W\gamma^*$	$13.6 \pm 2.4 \pm 4.3$
total background	$275.2 \pm 14.9 \pm 31.2$
signal + background	$958.8 \pm 15.7 \pm 58.3$
data	1111 ± 33

- Measured cross section for WW

7 TeV : $\sigma_{WW} = 52.4 \pm 2.0$ (stat.) ± 4.5 (syst.) ± 1.2 (lumi.) pb

Theoretical prediction: $\sigma_{NLO} = 47.0 \pm 2.0$ pb

8 TeV: $\sigma_{WW} = 69.9 \pm 2.8$ (stat.) ± 5.6 (syst.) ± 3.1 (lumi.) pb

Theoretical prediction: $\sigma_{NLO} = 57.3$ (+ 2.0 – 1.6)pb

WW cross section measurement

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Conclusions

- The cross section for the WW process was measured in the fully leptonic final state for the full 2011 dataset at a center of mass energy of 7 TeV and for the first 3.54 /fb 2012 data at 8 TeV

$$\sigma_{WW} = 52.4 \pm 2.0\,(\text{stat.}) \pm 4.5\,(\text{syst.}) \pm 1.2\,(\text{lumi.})\ \text{pb}$$

$$\sigma_{WW} = 69.9 \pm 2.8\,(\text{stat.}) \pm 5.6\,(\text{syst.}) \pm 3.1\,(\text{lumi.})\ \text{pb}$$

- The value for 7 TeV is 1-σ deviated from the theoretical prediction of 47±2.0 pb. For 8 TeV, it is more than 1-σ deviated from the prediction of 57.3 (+2.0–1.6) pb

- Benchmark analysis for the Higgs searches in the $H \to WW$ channel
  - Fully understanding of the main irreducible background
  - Validity of the methods

Higgs $\rightarrow$ WW Searches

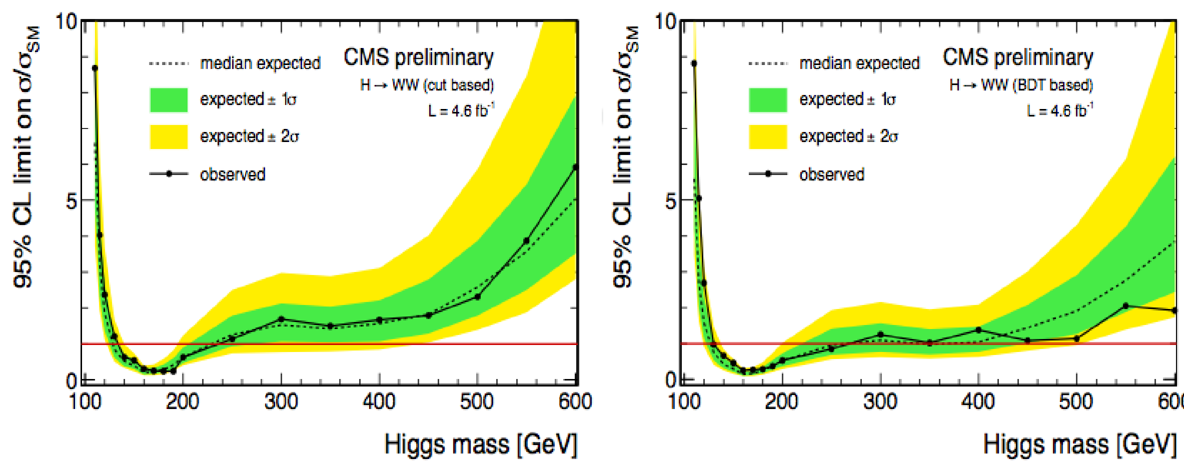
Higgs analysis overview

- The base analysis for the searches in the $H \to WW$ channel is the same as for the WW cross section measurement
  - Common object definition and efficiency measurements
    - Changed for 8 TeV: Muon and jet selection using MVA methods
  - Same data driven methods techniques
    - Changed for 8 TeV (Higgs): DY rejection using MVA variable

- WW process is now the background
  - Estimated in the Higgs region defining a pure WW control region for mH < 200 GeV
  - Measured scale factor to be applied on MC consistent to reproduce the measured cross section

Higgs analysis overview

- Two different approach are followed to set the limits for the Higgs mass: cut based analysis or shape analysis
- Cut based
  - Apply cuts on pT leptons, Δϕ, mll and mT → optimized for mH
  - Counting method
- Shape analysis
  - Fit the selected variable (BDT output) to extract the limit



(a) (b)

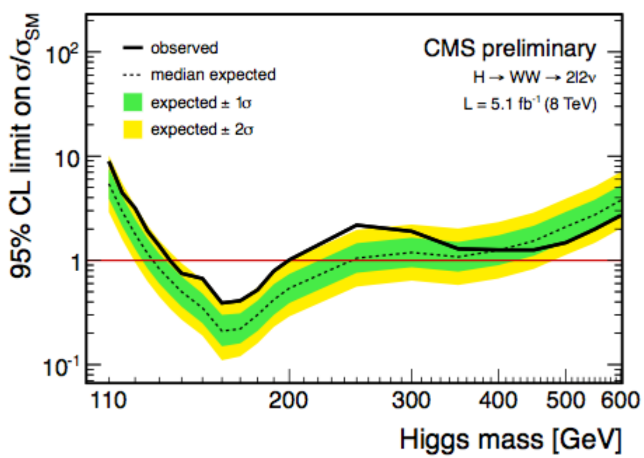
7 TeV results

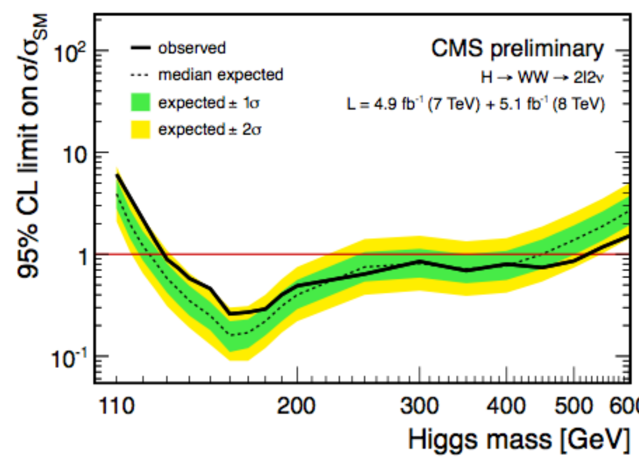
Figure 4: 95% expected and observed C.L. upper limits on the cross section times branching ratio, $\sigma_H \times BR(H \to W^+W^- \to 2\ell 2\nu)$, relative to the SM value using cut-based (a) and multivariate BDT (b) event selections. Results are obtained using the CLs approach.

Higgs analysis overview

- Combine the 7 and 8 TeV results for H → WW searches to set the limits in the Higgs boson mass
  - A small excess is observed for hypothetical low Higgs masses
  - Observed limits weaker than expected ones
  - Poor resolution in this channel, extended excess in the range

8 TeV results





7 + 8 TeV results

Figure 4: Expected and observed 95% CL upper limits on the cross section times branching fraction, $\sigma_H \times BR(H \to W^+W^-)$, relative to the SM Higgs expectation, using the 8 TeV data only (left) and the combined 7 TeV and 8 TeV data (right). Results are obtained using the CL_s approach.

Higgs

- Higgs searches with CMS using several decay channels
- Results presented on 4th July 2012 with 7 and 8 TeV results for γγ, bb, ττ, WW and ZZ
- Combine the 7 and 8 TeV results in the Higgs boson mass
- An excess of events is observed above the expected background with a local significance of 5 standard deviation for a mass of near 125 GeV
    - Expected significance for a SM Higgs boson with that mass is 5.8 standard deviations

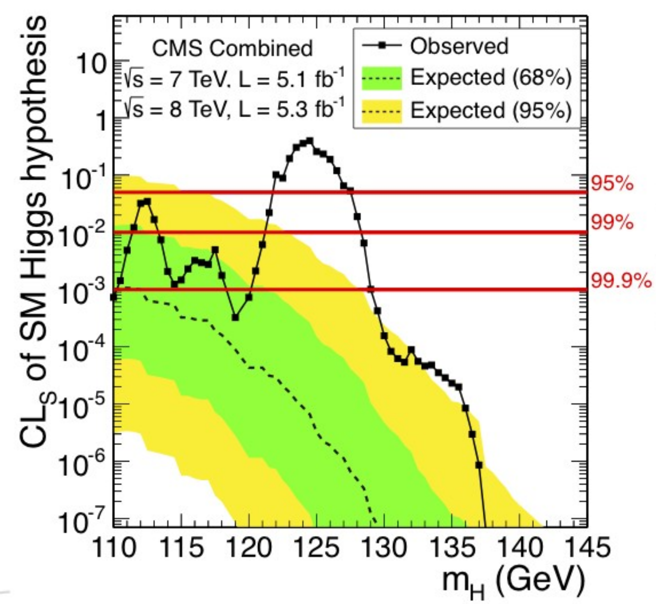


Figure 11: The CL_s values for the SM Higgs boson hypothesis as a function of the Higgs boson mass in the range 110–145 GeV. The background-only expectations are represented by their median (dashed line) and by the 68% and 95% CL bands.

Higgs

- Measure the mass of the discovered boson with the best mass resolution channels, γγ and ZZ
- These channels are also the ones with the higher significance
- Mass fit: 125.3 ± 0.4 (stat.) ± 0.5 (syst) GeV

Experiments at the LHC started to measure the new boson properties!!

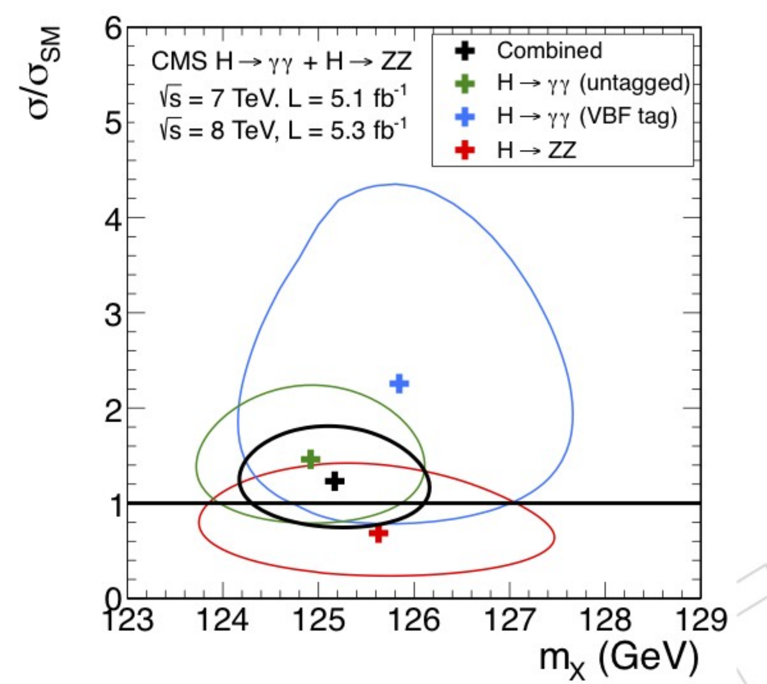


Figure 15: The 68% CL contours for a boson mass m_X and σ/σ_{SM} for the untagged $\gamma\gamma$, $\gamma\gamma$ with VBF-like dijet, 4ℓ, and their combination. The symbol σ denotes the production cross section times the relevant branching fractions. In this combination, the relative signal strengths for the three decay modes are constrained by the expectations for the SM Higgs boson.

Thanks!

Back-up

WW cross section measurement

References

SMP – 12 – 005 “*Measurement of WW production rate*" CDS Record: 1440234

AN – 12 – 036 “*WW cross section measurement in the Fully Leptonic Final State with 4.63 fb-1 at 7 TeV*”

HIG – 11 – 024 “*H → WW → 2l2nu*"

AN – 12 – 194 *“Search for the Higgs Boson Decaying to WW in the Fully Leptonic Final State at 8 TeV”*

HIG – 12 – 017 *“Search for the standard model Higgs boson decaying to W+W− in the fully leptonic final state in pp collisions at √s = 8 TeV”*

Muon Selection

- Muon Identification

Back to analysis flow

  - $p_T > 20$ GeV and $|\eta| < 2.4$
  - Global Muon OR Tracker Muon (TMLastStationTight)
  - $\chi 2$/ndof < 10 (Glb fit) . More than 10 hits in the inner tracker and at least one pixel hit
  - Kink finder $\chi 2$/ndof < 20
  - Relative p_T resolution better than 10%
  - $|d0| < 0.02$ cm and $|dz| < 0.1$ cm

- Muon Isolation
  - PF based isolation, PFIso, computed from the sum of the PF Candidates in $\Delta R < 0.3$ with
    - $p_T > 1.0$ GeV (neutral candidates)
    - $|dz(\text{candidate}) - dz(\text{muon})| < 0.1$ cm for charged candidates
  - $\text{PFIso}/p_T < 0.13$ (0.09) barrel (endcap)

Electron Selection

- Electron Identification

Back to analysis flow

  - p_T > 20 GeV and $|\eta|$ < 2.5
  - Cut based preselection imposed by trigger properties
    - $\sigma_{i\eta i\eta}$ < 0.01 (0.03) barrel (endcap)
    - $|\Delta\Phi_{in}|$< 0.15 (0.10) and $|\Delta\eta_{in}|$< 0.007 (0.009) and H/E < 0.12/0.10
    - Detector based relative ECAL HCAL and Tracker Iso < 0.2, 0.2, 0.2
  - BDT based ID working point described in AN 2011/413
    - Improves fake rejection wrt cut based ID
  - |d0| < 0.02 cm and |dz|< 0.1 cm
- Photon Conversion Rejection
  - Vertex fit probability with two tracks (one the electron) to be higher than 10^{-6}
  - Electron candidates must not have missing expected hits in the track

Electron Selection

- Electron Isolation

Back to analysis flow

  - PFIso, computed from the sum of the PF Candidates in $\Delta R < 0.4$ with
    - Inner footprint veto $\Delta R < 0.07$ ($\Delta\eta < 0.025$) neutral candidates (em)
    - $p_T > 1.0$ GeV (neutral candidates)
    - |dz(candidate) – dz(electron)| < 0.1 cm for charged candidates
  - PFIso/p_T < 0.13 (0.09)

MET Selection

- MET selection

Back to analysis flow

  - Increase the significance of the signal WW → llνν, genuine MET, versus the Z → ll+jets background, fake MET

- Fake MET affected by:
  - Increase of pile-up events → not constant over the Data / MC
  - Sensible to instrumental mis-measurements

- Construct two different projected METs

$$projectedE_{\mathrm{T}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi_{min} \geq \frac{\pi}{2} \\ E_{\mathrm{T}}^{\mathrm{miss}} \sin(\Delta\phi_{min}) & \text{if } \Delta\phi_{min} < \frac{\pi}{2} \end{cases}$$

$$\text{with } \Delta\phi_{min} = min(\Delta\phi(\ell_1, E_{\mathrm{T}}^{\mathrm{miss}}), \Delta\phi(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}}))$$

  - Projected pfMET: from pfMET
  - Projected tkMET: sum of charged PF candidates consistent with PV

  → *minprojectedMET* = min (projected pfMET, projected tkMET)

MET Selection

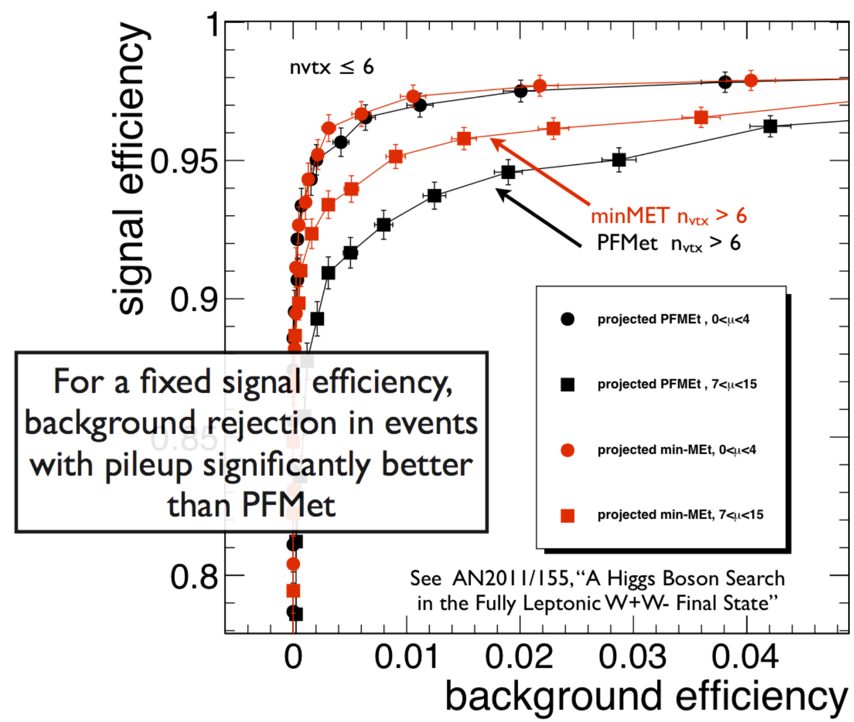
- MET selection – Cut

Back to analysis flow

  - To reduce pile-up dependence, define a nVtx dependant cut

  - *MinprojectedMET* > $\begin{cases} 37.0 + \text{nVtx}/2 \text{ GeV} – \text{same flavour} \\ 20.0 \text{ GeV} – \text{opposite flavour} \end{cases}$

Example of ROC figure from HWW analysis →



Jet Selection

- Jets objects

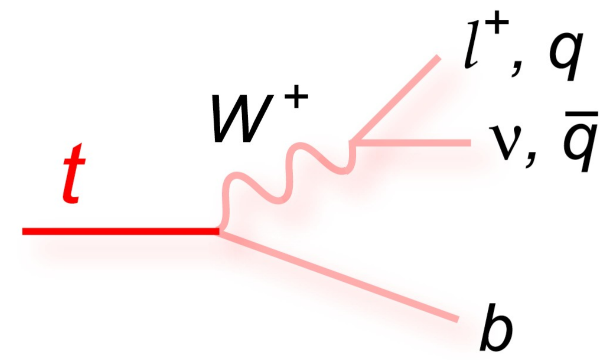
Back to analysis flow

  - PF Jets reconstructed with anti-kT clustering algorithm $\Delta R = 0.5$
  - Standard L2, L3 correction applied on top of L1
  - L1 corrected for pile-up with L1FastJet method

- Jets selection
  - $p_T > 30$ GeV and $|\eta|<5.0$
  - Reject events with more than zero jets
    - Reduce top background

Top Veto

Back to analysis flow

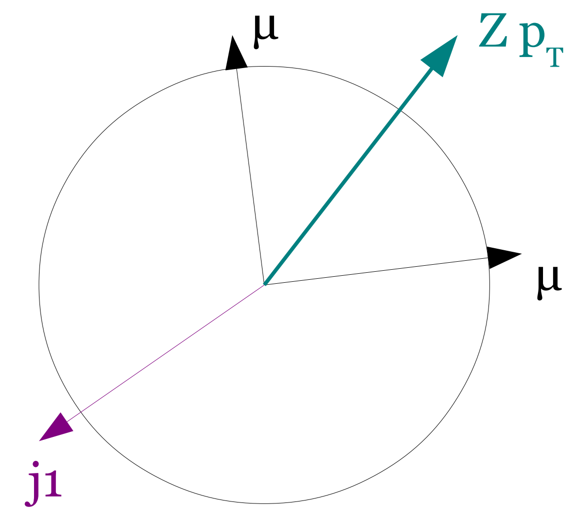


- Jet Veto is not enough to reject top background
  - Remaining background to be reduced using b-quark properties
- Further requirements are imposed to the event
  - Soft Muon veto
    - Reject events with a soft muon – consistent with a b-quark decay
    - $p_T > 3$ GeV, non isolated if $p_T > 20$ GeV
  - Low p_T jet b-tagging
    - Tag low p_T jets: $10 < pT < 30$ GeV
    - Tagging algorithm: Track Counting High Efficiency. TCHE > 2.1

Other selections

Back to analysis flow

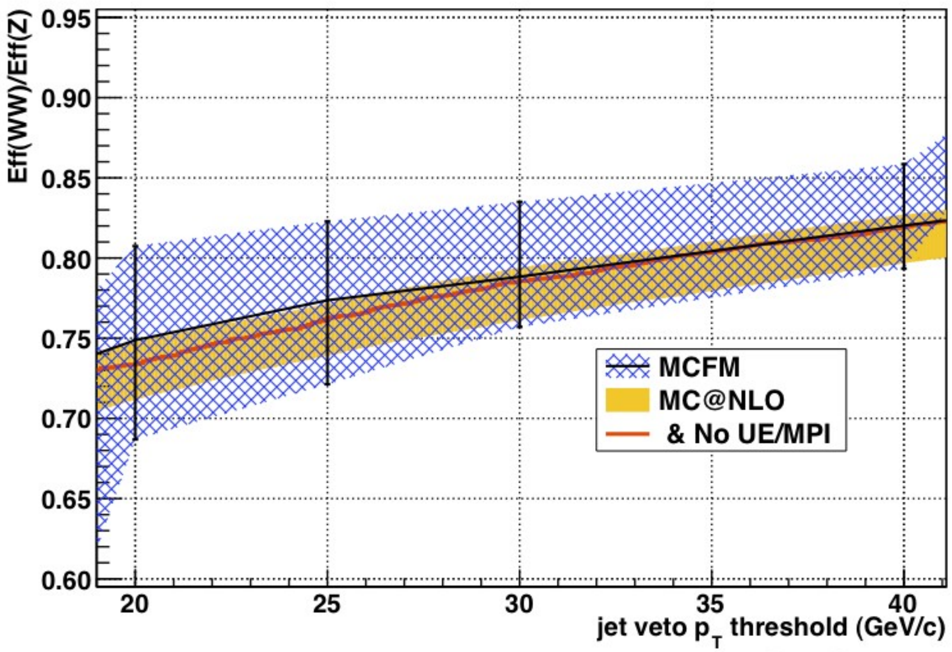
- Veto events with a third lepton to reduce diboson backgrounds WZ and ZZ
  - Lepton with tight ID and isolation requirements, but with $p_T > 10$ GeV
  - Near 100 % signal efficiency while removes 32 % WZ and 3 % ZZ
- Same flavour final states: ee and μμ
  - Drell Yan events: Z can recoil against jets in the event
  - Take advantage of the azimuthal angle Φ between the leading low p_T jet and the Z boson direction
  - Reject events with $\Delta\Phi(\,ll\,, j\,) > 165^{\circ}$
    - j: leading jet with $15 < p_T < 30$ GeV
    - ll: dilepton system → Z boson direction



- Kinematical cut $p_T(ll) > 45$ GeV
  - Further removes DY/Z backgrounds and fakes

Back to systematics

- The highest systematic in signal efficiency is the one from the jet veto efficiency
- The jet veto efficiency was measured on real Data events
  - $\varepsilon_{WW} = \varepsilon_{WW}^{MC} (\varepsilon_Z^{data}/\varepsilon_Z^{MC})$
- We studied the theoretical uncertainty from the ratio $\varepsilon_{WW}^{MC}/\varepsilon_Z^{MC}$
  - Vary the normalization (μR) and factorization (μF) scales by 0.5 and 2 times nominal
  - Take ratio of maximum WW and minimum Z and vice versa wrt nominal



- The systematic for jet veto efficiency is 4.6% for 30 GeV jets based on MCFM study

Top background estimation

- Also checked the per-channel results, considering the top veto efficiency estimated for the inclusive case
  - The sum over the four leptonic final states is the same as for the inclusive case – no surprises! :-)
  - Also consistency for of + sf

	$\mu\mu$	μe	eμ	ee
$\epsilon^{\mathrm{tW}}_{\mathrm{top-tag}}$	0.16 ± 0.02	0.16 ± 0.02	0.13 ± 0.01	0.16 ± 0.03
f_{tt} (%)	67 ± 11	66 ± 11	66 ± 11	66 ± 11
$\epsilon^{\mathrm{0-jet}}_{\mathrm{top-tag}}$ (%)	50.7 ± 3.7	50.3 ± 3.8	50.4 ± 3.1	50.5 ± 3.7
$\mathrm{N}^{\mathrm{Data-control}}_{\mathrm{btag}}$	46	46	40	30
$\mathrm{N}^{\mathrm{Bkg-control}}_{\mathrm{btag}}$	7.3 ± 1.1	8.0 ± 0.9	11.3 ± 1.5	4.9 ± 2.1
$\mathrm{N}^{\mathrm{signal}}_{\mathrm{top\ MC}}$	21.1 ± 1.0	27.5 ± 1.1	33.3 ± 1.2	14.7 ± 0.9
$\mathrm{N}^{\mathrm{signal}}_{\mathrm{top\ Data}}$	37.6 ± 8.7	37.5 ± 8.8	28.2 ± 7.7	24.5 ± 6.8
Data/MC Ratio	1.78	1.36	0.85	1.67